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LASER-ULTRASONIC MEASUREMENT OF ELASTIC PROPERTIES OF A THIN
SHEET AND OF TENSION APPLIED THEREON ;

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ABSTRACT:

A method and an apparatus for non-contact and non-invasive characterization of a moving thin
sheet and in particular of a paper web on a production line. The method uses a laser for the
generation of sonic and ultrasonic waves in the thin sheet and a speckle insensitive
interferometric device for the detection of these waves. The generation is performed in conditions
to avoid damage impeding further use of the sheet. When the generation and detection spots
overlap, the method provides a measurement of the compression modulus. When the generation
and detection spots are separated by a known distance and plate waves (Lamb waves) are
generated and detected, the method provides a measurement of the in-plane modulus and of the
tension applied to the sheet.   By detecting waves propagating in various directions, either by
rotating the detection sensor head or multiplexing the signals provided by several detection or
generation locations, the anisotropy of the in-plane modulus is determined.

LASER-ULTRASONIC MEASUREMENT OF ELASTIC PROPERTIES OF A THIN SHEET AND OF TENSION APPLIED THEREON

BACKGROUND OF THE INVENTION

5   **Field of the invention**

This invention relates to the determination of the elastic properties of a thin sheet and to the measurement by laser-ultrasonics of the tension applied to a thin sheet. This invention is particularly useful for paper making and printing.

Description of prior art

10   There is currently a great interest in industry to measure the elastic properties of thin sheets, either on the manufacturing line or off-line and to evaluate the tension applied to these thin sheets during processing. These measurements are particularly important for papermaking and printing as well as for aluminum foil rolling and plastic sheet fabrication. Regarding papermaking and printing, adequate tension applied to

15   the web is fundamental for avoiding breaks and insuring optimum runnability. The in-plane elastic modulus of a paper web and its variation with direction are also important parameters to measure for evaluating the paper web quality. They are usually measured off-line with an apparatus that measures a parameter related to the in-plane modulus and called the tensile stiffness index (TSI). More precisely the

20   TSI in a given direction is defined as the square of the acoustic velocity in this direction. The variation of the TSI with direction and the direction of its maximum value, called the Tensile Stiffness Orientation parameter (TSO), are also evaluated with this off-line apparatus. The paper web compressibility is also of interest, especially for printing, and can be estimated by through-thickness elastic modulus

25   measurements.

Regarding the measurement of the tension applied on a thin sheet, the conventional method is to measure the load the sheet causes on a roller. Consequently, only the mean value over the sheet width is accessible and local tension peaks cannot be

30   measured. To evaluate the variation of tension across a sheet, particularly across a paper web, sensors based on an applied force, sound waves or applied pressure have been designed. These sensors do not usually meet all the requirements of industry to measure the tension on a paper web running at high speed, as reviewed by H. Linna and P. Moilanen in *Comparison of methods for measuring web tension,*

35   *Tappi Journal*, vol. 71, p. 134-138 (1988). They have prohibitive characteristics such

as being slow, invasive, and sensitive to temperature changes. Although piezoelectric transducers have been developed for on-machine measurements, they have the drawback to be based on a contact approach. A non-contact method to measure the tension applied to a paper web was proposed by M. Luukkala and T.

5   Marttinen in US Patent # 4, 833, 928 entitled *Method and apparatus for noncontacting tension measurement in a flat foil and especially in a paper web*. The method is based on the generation of a sound wave by a piezoelectric transducer or a microphone and the detection of this sound wave by a laser-based triangulation technique. Although an improvement over other methods, the method proposed by

10   M. Luukkala et al. suffers from the low sensitivity of laser-based triangulation techniques to acoustic motion.

Regarding the measurement of the elastic properties, various techniques for measuring the elastic properties of a static or moving paper web were recently

15   reviewed in a publication by P.H. Brodeur, M.A. Johnson, Y.H. Berthelot, J.P. Gerhardstein, entitled *Noncontact laser generation and detection of Lamb waves in paper*, published in the Journal of Pulp and Paper Science, 23, J238, (1997). We summarize hereinbelow the main elements of this review. Contact methods based on a mechanical sensor for force measurement, ultrasonic transducers for Lamb

20   wave generation and detection and friction-induced noise generator and microphone detection have been developed. As mentioned before, contact methods are not suitable for on-line measurement on a paper web moving at high speed. Two non-contact approaches have been investigated. The first method is based on air-coupled transducers to generate and detect ultrasonic and sonic waves propagating

25   across the web. The reliability of this method is limited by the effect of ultrasonic absorption in air, sensitivity to moisture and air turbulence. The second method relies on lasers to generate and detect ultrasonic and sonic Lamb waves propagating across the web. Laser measurements of the ultrasonic and sonic surface motion of the paper web can be performed by laser-based triangulation methods and by

30   interferometric methods, the later being much more sensitive. These laser methods have been described in various patents and publications and are discussed below.

The generation of acoustic waves has been reported to be performed by a Nd:YAG laser operated at its fundamental wavelength in the near infrared or at its second

35   harmonic in the visible in US patent # 4, 622, 853 by M.A. Leugers entitled *Laser*

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induced acoustic generation for sonic modulus and in US patent # 5, 814, 730 by P.H. Brodeur, Y.H. Berthelot, J.P. Gerhardstein, M.A. Johnson entitled *Material characteristic testing method apparatus using interferometry to detect ultrasonic signals in a web* and also in the publication of B. Pouet, E. Lafond, B. Pufahl, D.

5   Bacher, P. Brodeur, M.B. Klein entitled *On-machine characterization of moving paper using a photo-electromotive force laser ultrasonic method* published in Proceeding of SPIE, vol. 3589, p. 160, (1999). The use of an ultraviolet nitrogen laser was reported in US patent # 4, 674, 332 by S. A. Pace, S. S. Salama entitled *Laser induced acoustic generation for sonic modulus*. These two lasers, Nd-YAG

10   and N_2 produce strongly fluctuating measurements from laser shot to laser shot and tend to induce damage on the paper web, as recognized by Y. H. Berthelot and M.A. Johnson in *Laser ultrasonics in copy paper*, Optical Engineering, vol. 36, pp. 408-416, (1997). In US patent # 5, 025, 665 entitled *Non-contacting on-line paper strength measuring system*, M. A. Keyes IV, W. L. Thompson considered the use of

15   an infrared CO_2 laser (around a wavelength of 10 µm) with very long pulses, but this disclosure failed to indicate and discuss why this wavelength could be more appropriate for damage free generation of ultrasound in paper.

Regarding the detection of laser generated ultrasound, several methods were
20   proposed in the patents and publications mentioned above. Detection can be performed by using a contact piezoelectric transducer or a microphone as proposed by M. A. Leugers in US patent #4,622,853 and S. A. Pace, S. S. Salama in US patent #4,674,332, or by using non-contact laser-based methods. As already mentioned, contact methods are not suitable for on-line measurements on a moving

25   paper web. The non-contact methods proposed are either based on laser triangulation (M. A. Keyes IV, W.L. Thompson in US patent # 5, 025, 665), speckle sensitive interferometric heterodyne detection of the phase modulation produced by the ultrasonic motion of the paper web (P. H. Brodeur, Y. H. Berthelot, J. P. Gerhardstein, M. A. Johnson in US patent # 5,814,730) or a speckle insensitive

30   photo-electromotive force based demodulator (B. Pouet et al, publication mentioned above). The heterodyne interferometric method used is sensitive to the speckle structure of the collected light, which results in a strongly fluctuating light level collected from the surface and a very large increase of the intensity noise seen by the optical detector. The speckle insensitive photo-electromotive force can be a

35   basis of a laser-ultrasonic system for paper characterization, although the data

reported with this device appears very noisy when the sheet is in rapid motion. Data is also only reported for the cross-machine direction. In the machine direction the Doppler effect produced by the sheet motion will decrease even more the signal-to-noise ratio.

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In conclusion, all the previously described methods and techniques to either measure the tension or the mechanical properties of a sheet in motion (in particular a paper web) have drawbacks which limit their practical use. We have realized that laser-based generation and detection methods (called laser-ultrasonics) have the

10   key advantage of being non-contact. We performed several experiments on static and moving paper sheets. For these experiments, a laser was selected that generated ultrasound in a reproducible manner without damaging the paper. The detection was performed using a confocal Fabry-Perot interferometer insensitive to the speckle structure of the collected light.

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For most of the experiments, the samples were sheets of standard copy paper but other types of paper sheets were also tested positively. Tensions up to 1400 N/m were applied to the sheet of paper using calibrated weights. Data was analyzed by considering the sheet of paper as a vibrating membrane with stiffness. Assuming

20   known the basis weight and the thickness of the paper sheet, an effective in-plane Young's modulus and the applied tension were determined. Measurements of the out-of-plane compression modulus were also reported.

In another set of experiments, the elastic properties of a paper web sheet were

25   probed using the same basic setup. The in-plane sonic and ultrasonic displacement associated to the S_o Lamb wave mode was detected using a detection laser impinging at an oblique incidence on the sheet. In-plane displacements induced by acoustic waves propagating in different directions were measured with a head mounted on a computer controlled rotation stage

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SUMMARY OF THE INVENTION

According to the invention, there is provided a method for non-contact characterization of a sheet of material, preferably a sheet moving relative to the

35   analyzing apparatus. The method involves the steps of irradiating the sheet with a

beam of light at a first location to create an acoustic wave in the sheet; irradiating the sheet with a second different beam at a second location on the sheet; and demodulating the second beam to detect a signature of the acoustic wave within the second beam, the signature being characteristic of a property of the sheet.

5   Further, according to the invention, there is provided an apparatus for non-contact and non-invasive characterization of a sheet, the sheet preferably moving relative to the apparatus, the apparatus comprising: a first means for illuminating a first location of the sheet with a first beam and for generating acoustic waves propagating through the sheet thickness and over its surface,

10   a second means for illuminating a second location of the sheet with a second beam, on the same side or opposite side of the sheet, the second location being spaced from the first location by a predetermined distance, the sheet scattering the second beam to produce a scattered beam having a plurality of speckles, means for collecting the scattered beam, such collected beam having a phase and

15   frequency modulation representative of the acoustic motion at this second location, and for demodulating the phase and frequency modulation to provide a signal representative of the acoustic motion at the second location, and analyzing means for analyzing the signal so as to determine a characteristic or a set of characteristics of the sheet.

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BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and for further objects and advantages thereof, reference may be made to the following description taken in

25   conjunction with the accompanying drawings in which:

Fig. 1 is a schematic block diagram illustrating a sonic and ultrasonic generation and detection apparatus for measurement of the out-of-plane acoustic displacement of a thin sheet, wherein the detection laser is normal to the surface of the thin sheet

30   and the collection of the light scattered or reflected by the thin sheet is also in a normal direction;

Fig. 2 shows a plot of the group velocity dispersion obtained experimentally on a sheet of paper and the theoretical fit;

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Fig. 3 is a schematic block diagram illustrating a sonic and ultrasonic generation and detection apparatus for the measurement of the out-of-plane and in-plane acoustic displacements of a thin sheet, wherein the detection laser is normal to the surface of the thin sheet and the light scattered by the sheet is collected along an

5   oblique direction;

Fig. 4 is a schematic block diagram illustrating a sonic and ultrasonic generation and detection apparatus for the measurement of the out-of-plane and in-plane acoustic displacements of a thin sheet, wherein the detection laser is oblique to the

10   surface of the thin sheet and the light scattered by the thin sheet is collected along the same direction as the detection laser;

Fig. 5 shows the polar plots of the Tensile Stiffness Index (TSI) of a sheet of paper measured in static and dynamic conditions (paper velocity 11 m/s);

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Fig. 6 is a schematic block diagram illustrating a multiple detection head apparatus for the detection of the out-of-plane and in-plane acoustic displacements of a thin sheet; and

20   Fig. 7 is a schematic diagram of an embodiment of the apparatus of the invention with a noise correction unit.

DETAILED DESCRIPTION OF THE PREFERRED
EMBODIMENTS OF THE INVENTION

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Fig. 1 shows a first embodiment according to the invention in which a beam 12 from a laser 10 is sent onto a moving thin sheet 14 and generates sonic and ultrasonic waves propagating throughout the sheet. This embodiment, as it will be explained below, is particularly appropriate for the measurement of the tension applied to the

30   sheet. Generation is based on a thermoelastic mechanism: laser light is absorbed by the sheet, absorbed energy produces a transient heat source, which in turn, by thermal expansion, produces transient forces at the source of the launched acoustic waves. The types of waves launched are plate waves, essentially the anti-symmetric wave A_0 and the symmetric wave S_0, and a longitudinal bulk wave propagating

35   through the thickness of the sheet. A_0 and S_0 are dispersive waves i.e. their

velocities (phase or group velocities) are frequency dependent. At low frequencies S_0 is practically non-dispersive and is essentially an extensional wave having only in-plane displacement. A_0 is strongly dispersive at low frequencies and its velocity vanishes at zero frequency unless a tension is applied to the sheet. In this low

5   frequency range, the antisymmetric wave becomes a non-dispersive membrane wave as described in the textbook *Theoretical Acoustics* (McGraw Hill, New-York) by P. M. Morse and K. U. Ingard and its phase velocity (v_p) is only determined by the applied tension T and the mass per unit area σ (called basis weight in the paper industry):

$$v_p = \sqrt{\frac{T}{\sigma}}$$

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This formula is the basis of the tension determination, although a more elaborate analysis that takes into account membrane stiffness is needed in practice as explained below.

15   The generation laser used in our method is preferably selected such as to produce on the sheet no adverse mark that could impede subsequent use of the sheet. In the case of paper used for printing there should be no laser mark that appears after printing. We found that a TEA carbon dioxide laser operating around 10.6 μm is very appropriate for generation on paper without any damage. The energy density on the

20   sheet has however to be limited to some threshold value. This value is lower for quality paper used for fine prints than for standard copy paper or newsprint paper. The carbon dioxide laser is also suitable for generation on polymer films. In both cases the performance of the TEA CO_2 laser is explained by its relatively long pulse (100 ns typically) and the progressive absorption of laser light below the surface,

25   which produces a heat source and an acoustic source distributed below the surface and in turn, strong acoustic emission without damage. Much shorter pulse and high peak power lasers operating in the near infrared, such as the Nd-YAG, or in the visible or ultraviolet range tend to ablate the surface and are not generally suitable. Other lasers that operate at a wavelength absorbed by the material could also be

30   suitable. For paper, we note in particular the Erbium-YAG laser operating around 2.9 μm, a wavelength that is absorbed by the OH-stretch band of cellulose fibers. In the case of metal sheets, non-invasive strong generation is more difficult with any laser

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and the laser power density has to be drastically limited to avoid any damage, so generation stays within the thermoelastic regime.

5   The generation laser is shown in Fig. 1 to be directly coupled to the sheet. It could also be coupled through an optical fiber. Present technological limitations will make this fiber rather short in case of the TEA CO_2 (typically one meter). Much longer lengths (several tens of meters) are readily feasible with shorter wavelength lasers such as the Erbium-YAG, thus making it possible to have the laser located far away of the production line.

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As shown in Fig. 1, a beam 16 from a second laser 18 is used for detection of the acoustic motion of the sheet 14 and it impinges on the sheet at normal incidence after reflection by a mirror 20. In Figure 1, this laser beam 16 is shown to be transmitted by an optical fiber 22, which is usually readily feasible since this laser is

15   usually in the visible or near-infrared range (such as the Nd-YAG laser operating at 1.06 μm). The laser beam can also be directly coupled. The two laser beams 12, 16 impinge on the moving sheet 14 at different locations separated by a known distance. The two laser beams are shown to illuminate the sheet from the same side, but since the acoustic wave generated and detected is a plate or Lamb wave and

20   involves motion of the whole sheet, the two beams could be as well on opposite sides of the sheet. The light from the detection laser scattered off the thin sheet is then collected by a lens 24 and transmitted by an optical fiber 26 to a large étendue (throughput) speckle insensitive interferometric demodulator 28. The demodulator includes an optical detector (not illustrated) that provides an electrical signal

25   representative of the acoustic motion of the sheet. This signal is then digitized and processed by a digital sampling and processing unit 30. The demodulator could be a confocal Fabry-Perot interferometer used in transmission or reflection (for a very thin sheet) as described in US patents # 4,659,224 and # 4,966,459 (J.-P. Monchalin) and US patent # 5,137,361 (R. Héon and J.-P. Monchalin). Alternatively, a two-wave

30   mixing scheme in a photorefractive crystal could be used as described in US patent # 5,131,748 by J.-P. Monchalin and R. K. Ing and US patent # 5,680,212 by A. Blouin, P. Delaye, D. Drolet, J.-P. Monchalin and G. Roosen. The Fabry-Perot scheme is usually preferred whenever the sheet is rough and is in rapid motion, such as a paper web, or is affected by large vibrations, since this scheme has a more

35   rapid response for adaptation to a change of the speckle pattern and is more tolerant

to change of the frequency of the scattered light caused by a vibrating motion of the sheet (Doppler effect). It also possible to use, although usually with a lesser sensitivity, a very simple demodulator based on the photoelectromotive force effect, as described by M. P. Petrov, I. A. Sokolov, S. I. Stepanov, G. S. Trofimov, in

5   Journal of Applied Physics, vol. 68, p 2216, 1990 entitled *Non-steady-state photo-electromotive-force induced by dynamic gratings in partially compensated photoconductors*. It should be noted that it is very important in the case of a sheet like paper to use a speckle insensitive large étendue interferometer. The large number of speckles collected in this case minimizes the noise introduced by the

10   sheet motion. In the case of a speckle sensitive interferometer, as used by Brodeur et al. (US patent # 5,814,730) this noise would have been extremely large, as mentioned previously.

Furthermore we found that in the case of paper, the noise that appears at the output

15   of the demodulator for a paper sheet in motion is essentially intensity noise and consequently could be subtracted from the signal at the output of the demodulator. To perform this correction a detector 42 (Fig. 7) with the same detection bandwidth as the one of the demodulator is set ahead of the demodulator 28 and picks up through a beam splitter 44 a fraction of the light sent onto the demodulator. The

20   signal from this additional detector is then subtracted from the signal of the demodulator with a differential amplifier 46 to provide an electrical signal substantially free of the intensity fluctuations caused by the sheet motion. This is strictly valid at sufficiently low frequencies for which the frequency response to amplitude modulation of the demodulator (especially confocal Fabry-Perot) is

25   essentially flat, otherwise one should take into account this response. Alternatively one could use a demodulator insensitive to intensity fluctuations such a demodulator with a differential detection scheme, as described in US patent # 5,080,491 by J.-P. Monchalin and R. Héon for the Fabry-Perot or a two-wave mixing scheme (see US patents # 5,131,748 and # 5,680,212 mentioned above) or a photo electromotive

30   force scheme. An alternative to this compensation scheme, which also diminishes the noise of any origin, is to average signals obtained at various times during sheet motion. Averaging could also be used in addition to the compensation scheme to improve further the signal-to-noise ratio.

In the embodiment of Fig. 1, the normal incidence of the detection beam and the normal collection of the scattered laser light allow to detect only the out-of-plane sonic and ultrasonic displacements produced by the generation laser. Alternatively the direction of incidence of the detection beam and the direction of light collection

5   could be symmetric with respect to the normal of the sheet and only out-of-plane displacements would be detected. This out-of-plane displacement is related to the A_0 Lamb wave mode of the sheet. Since the distance between the generation and detection spots is known the phase and group velocities of the A_0 mode can be obtained from the time delay between generation and detection of the displacement.

10   The phase velocity v_p of the A_0 ultrasonic wave propagating on a membrane can be found in the publication by S. W. Wenzel and R.W. White, *A Multisensor Employing an Ultrasonic Lamb-Wave Oscillator*, IEEE Journal of Quantum Electronics, vol. 35, p. 735, (1988) and is given by:

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$$v_p = \sqrt{\frac{T}{2\sigma} + \sqrt{\left(\frac{T}{2\sigma}\right)^2 + \frac{\pi^2 f^2 d^3 Y_f}{3\sigma}}} \quad \text{with } Y_f = \frac{Y}{1-v^2}$$

where d is the thickness of the thin sheet, f is the frequency of the ultrasonic wave, T is the applied tension, σ is the basis weight, Y is the in-plane Young's modulus (a measure of the stiffness of the sheet) and v is the Poisson ratio. Experimentally, we

20   can obtain the phase velocity by measuring the phase delay of the acoustic waves propagating over a known distance. This usually requires to measure the signal at two different detection points since the initial phase, at the generation point, is unknown. Alternatively, the measurement of the group velocity v_g necessitates only one detection point, since it is insensitive to the initial phase. Hence, knowing the

25   propagation distance between the generation and the detection points, the group velocity can be determined. More precisely, the dispersion of the ultrasonic group velocity can be extracted from the laser-ultrasonic data using the method described by J.-D. Aussel in US patent # 5,035,144 entitled *Frequency broadband measurement of the characteristics of acoustic waves*. From the relation between the

30   phase and the group velocities given below:

$$v_g = \frac{v_p^2}{v_p - f\dfrac{dv_p}{df}}.$$

and the previous equation, we obtain readily the equation giving the group velocity as a function of tension, of the effective Young's modulus Y_f, of the basis weight and the thickness. Assuming the basis weight and the thickness of the sheet known, the

5   value of the effective Young's modulus Y_f and of the tension applied to the sheet are then obtained from a fit of the equation giving the group velocity to the experimental data. Note that the tension is essentially determined by the asymptotic low frequency value. An example of such a fit to experimental data is shown in Figure 2 for a sheet of standard copy paper.

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In the case of a null distance between generation and detection spots, which means superimposed spots, through thickness echoes are observed. From the measurements of the time-of-flight, the through-thickness velocity (v_L) is determined, assuming known the thickness d. Assuming further known the basis weight σ, the

15   compression modulus or elastic constant C_{11} is then determined by the well known equation:

$$C_{11} = \frac{V_L^2 \sigma}{d}$$

the symbols being as explained above.

20   In a second embodiment shown in Fig. 3, the light scattered off the thin sheet is collected at an oblique incidence. In this embodiment, both the out-of-plane and the in-plane sonic and ultrasonic displacements are measured. The in-plane ultrasonic and sonic displacements are related to the S_o Lamb wave mode of the sheet. Since the distance between the generation and detection spots is known the phase and

25   group velocities of the S_o mode can be obtained from the time delay between generation and detection. The in-plane stiffness or Young modulus of the sheet can be derived from these measurements. More precisely, in the case of paper, the tensile stiffness index (TSI) in a given direction (defined as the square of the acoustic velocity in this direction) is obtained from these measurements. Note that it is

30   possible to detect simultaneously the two waves A_o and S_o waves because they have very different velocities and S_o actually arrives much earlier than A_o.

Alternatively instead of having the illuminating beam for detection normal to the sheet and detection at an angle, the detection direction could be normal and the illuminating beam can be directed at an angle.

5   In a third embodiment shown in figure 4, the detection laser impinges on the sheet at an oblique incidence and the light scattered off the thin sheet is collected along the same oblique incidence. In this embodiment, both the out-of-plane and the in-plane sonic and ultrasonic displacements are also measured. In this embodiment the sensitivity to in-plane displacement is doubled compared to the embodiment of figure

10   3.

Since it is of interest to measure the modulus and the tension in various directions, the detection assembly shown in Figs. 3 and 4 can be mounted on a computer controlled rotation stage to allow the measurements of these parameters as a

15   function of direction. In particular, in the case of paper, the variation of the TSI with direction and the direction of its maximum value, called the Tensile Stiffness Orientation parameter (TSO), can be determined in this way. An example of data obtained with this technique on a paper sheet is shown in figure 5. Figure 5 actually plots the TSI as a function of direction for the sheet stationary and for the sheet in

20   motion at a velocity of 11 m/s. For this data, a TEA CO_2 laser was used for generation and a confocal Fabry-Perot for detection. This data demonstrates the capability of our technique to measure the TSI of a paper sheet in rapid motion and it should be noted that these results were obtained without any damage to the sheet.

25   This determination can also be performed without a rotating part by an optical multiplexing scheme as shown in Figure 6. The detection laser 18 is coupled through a large core multimode fiber 32 which is then split into three fibers 33, 34, 35 to give three beams that impinge on the sheet at locations D_1, D_2 and D_3. Scattered light is then collected by three large core multimode fibers 37, 38, 39 that are fused into a

30   single fiber 40, which finally couples the received light onto the demodulator 28. The illumination and the detection directions are properly tilted to detect both A_0 and S_0 waves. The locations of D_1, D_2 and D_3 with respect to the generation spot 36 are such that one detects the acoustic wave traveling in the machine direction (with D_1), the wave traveling at 45° to the machine direction (with D_2) and the wave traveling at

35   90° in the cross-machine direction (with D_3). These three detection spots are also

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located at different distances from the generation spot 36 to introduce a time delay between the arrivals of the acoustic waves from different directions. Hence, as shown in Figure 6, a single detection channel can be used and the signal associated to a given direction is well separated from the others in the output signal. This three-

5   channel configuration allows therefore measurement of the anisotropy of the in-plane stiffness without any rotating part. This multiplexing method was illustrated in Fig. 3 by showing three different locations, but obviously more locations could be used so as to improve the resolution and accuracy of the determination of the anisotropy of the in-plane stiffness. Alternatively, the generation laser beam 12 can be separated

10   in several beams that impinge on the sheet at different locations. These generation locations define with the single detection spot different directions of measurement. The generation spots are also located at different distances from the detection spot, so as to introduce time delays to separate the contributions from the various directions. Another alternative, while using a single generation location and several

15   detection spots, is to use an array of demodulators of large étendue, as described in the US patent # 5, 402, 235, *Imaging of ultrasonic-surface motion by optical multiplexing* by J.-P. Monchalin. In this case the three (or more) collection fibers shown in Fig. 6 would not be fused together but will transmit their light signals to distinct elements of the array.

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Finally it is noted that, except when measuring in the cross-machine direction (perpendicular or transverse to the direction of motion of the sheet), a correction is made on the measured acoustic velocity to take into account the velocity of the sheet itself, which is always known with sufficient accuracy. This correction is nearly

25   negligible for the S_0 wave but is significant for A_0.

Claims:

1. A method for non-contact characterization of a sheet of material, comprising the
   steps of:

5   i)   irradiating the sheet with a first beam at a first location to create an acoustic
           wave in the sheet;

     ii)   irradiating said sheet with a second beam at a second different location on
           the sheet, and

     iii) demodulating the second beam to detect a signature of the acoustic wave
10   within the second beam, the signature being characteristic of a property of
           the sheet.

2. A method for non-contact characterization of a moving sheet, comprising the
   steps of:

     - illuminating the sheet at a first location with a first laser beam for generating
15   acoustic waves propagating through the sheet thickness and over its surface,

     - illuminating the sheet at a second location with a second laser beam, on the
   same side or the opposite side of the sheet, this second location being spaced from
   the first location by a predetermined distance, said sheet scattering the second
   beam to produce a scattered beam with a plurality of speckles,

20   - collecting the scattered beam, such collected scattered beam having a
   phase or frequency modulation representative of the acoustic motion at the second
   location,

     - demodulating the phase or frequency modulation with an interferometer
   substantially insensitive to speckles, so as to provide an electrical signal
25   representative of the acoustic motion at the second location, and

     -    analyzing the electrical signal to determine a characteristic or a set of
          characteristics of the moving sheet.

3.   The method of claim 1 or 2 wherein said first beam has properties preventing
   a damage of the sheet affecting further use thereof.

30 4. A method as described in claim 1 whereby the sheet is a paper web.

5. A method as described in claim 4 whereby the sheet is a paper web used for
   printing.

6. A method as described in claim 1 whereby the sheet is of a polymer.

7. A method as described in claim 1 whereby the sheet is of metal.

8. A method as described in claim 2 whereby the characteristic is the tension applied to the sheet.

9. A method as described in claim 2 whereby the characteristic is an elastic modulus.

10. A method as described in claim 2 whereby the set of characteristics consists in the variation of the in-plane elastic modulus in various directions.

11. A method as described in claim 2 and applied to a paper web whereby, the set of characteristics is the Tensile Stiffness Index in various directions of the paper web.

12. A method as described in claim 1 or 2 including further the averaging of signals obtained at various times during sheet motion to further minimize additional noise introduced by sheet motion.

13. A method as described in claim 1 or 2 whereby additional noise introduced by sheet motion is substantially diminished by subtracting a signal representative of the fluctuations of intensity of the collected light prior to demodulation.

14. A method as described in claim 1 whereby second laser beam is sent substantially perpendicular to the sheet surface and scattered light is collected in a direction also substantially perpendicular to the sheet surface or second laser beam and collection direction are at an angle and are substantially symmetric with respect to the normal to the sheet surface to detect through thickness ultrasonic motion or out-of-plane motion associated to the A_0 Lamb acoustic wave.

15. A method as described in claim 1 whereby the second laser beam is directed substantially perpendicular to the sheet surface and the scattered beam is collected at an angle or the other way around or both are substantially in the same direction at an angle with respect to the normal to the sheet to detect in-plane acoustic motion associated to S_0 Lamb ultrasonic wave.

16. A method as described in claim 1 whereby second laser beam is sent substantially perpendicular to the sheet surface and scattered light is collected at an angle or the other way around or both are substantially in the same direction at an angle with respect to the normal to the sheet to detect both out-of-plane and in-plane acoustic motion.

17. A method as described in claim 2 whereby the step of signal analyzing consists of deriving the tension applied to the sheet from the asymptotic low frequency

value of the phase or group velocity dispersion curve calculated from the out-of-plane displacement signal associated to the A_0 Lamb wave mode.

18. A method as described in claim 2 whereby the step of signal analyzing consists of deriving the in-plane modulus from the velocity calculated from the in-plane displacement signal associated to the S_0 Lamb wave mode.

19. A method as described in claim 1or 2 whereby the second location overlaps the first location and whereby signal analysis consists in deducing from the through-thickness echoes the through-thickness velocity and from the through-thickness velocity the compression modulus or compressibility.

20. A method as described in claim 1 whereby several detection locations are used to measure simultaneously the velocity of S_0 and A_0 modes in various directions and to obtain the angular distribution of tension and tensile modulus.

21. A method as described in claim 1 whereby several generation locations are used to measure simultaneously the velocity of S_0 and A_0 modes in various directions and to obtain the angular distribution of tension and tensile modulus.

22. An apparatus for non-contact and non-invasive characterization of a sheet, comprising:

   - a first means for illuminating a first location of the sheet with a first beam and for generating acoustic waves propagating through the sheet thickness and over its surface,

   - a second means for illuminating a second location of the sheet with a second beam, on the same side or the opposite side, the second location being spaced from the first location by a predetermined distance, the sheet scattering the second beam to produce a scattered beam having a plurality of speckles,

   - a third means for collecting the scattered beam, such collected light having a phase or frequency modulation representative of the acoustic motion at this second location,

   - interferometric means substantially insensitive to speckles for demodulating this phase or frequency modulation, so as to provide an electrical signal representative of the acoustic motion at this second location, and

   - analyzing means for analyzing the electrical signal so as to determine a characteristic or a set of characteristics of the moving sheet.

23. An apparatus as described in claim 22 whereby the sheet is a moving paper web.

24. An apparatus as described in claim 23 whereby the sheet is a paper web used for printing.

25. An apparatus as described in claim 22 whereby the sheet is of a polymer

26. An apparatus as described in claim 22 whereby the sheet is of a metal.

27. An apparatus as described in claim 22 whereby the characteristic is the tension applied to the sheet.

28. An apparatus as described in claim 22 whereby the characteristic is an elastic modulus.

29. An apparatus as described in claim 22 whereby the set of characteristics consists in the variation of the in-plane elastic modulus in various directions.

30. An apparatus as described in claim 22 and used on a paper web whereby the set of characteristics is the Tensile Stiffness Index in various directions of the paper web.

31. An apparatus as described in claim 22 further including averaging means acting on the signals obtained at various times during sheet motion and used prior to analysis to further minimize additional noise introduced by sheet motion.

32. An apparatus as described in claim 22, including further detector means to measure the fluctuations of intensity ahead of interferometric means and subtraction means to subtract detector means signal from said electrical signal to minimize additional noise introduced by sheet motion.

33. An apparatus as described in claim 22 whereby second means sends second laser beam substantially perpendicular to the sheet surface and third means collects scattered light in a direction also substantially perpendicular to the sheet surface or second means sends laser beam at an angle and third means collects scattered light in a direction substantially symmetric with respect to the normal to the sheet surface to detect through thickness ultrasonic motion or out-of-plane motion associated to the A_0 Lamb acoustic wave.

34. An apparatus as described in claim 22 whereby second means sends second laser beam in a direction making an angle with respect to the sheet surface and third means collects scattered light in a direction substantially normal to the sheet surface or the other way around or both means have directions substantially the same and making an angle with respect to the sheet surface to detect in-plane acoustic motion associated to S_0 Lamb acoustic wave.

35. An apparatus as described in claim 22 whereby second means sends second laser beam in a direction making an angle with respect to the sheet surface and third means collects scattered light in a direction substantially normal to the sheet surface or the other way around or both means have directions substantially the

same and making an angle with respect to the sheet surface to detect both out-of-plane and in-plane acoustic motion.

36. An apparatus as described in claim 22 whereby the analyzing means derives the tension applied to the sheet from the asymptotic low frequency value of the

5 phase or group velocity dispersion curve calculated from the out-of-plane displacement signal associated to the A_0 Lamb wave mode.

37. An apparatus as described in claim 22 whereby the signal analysis means derives the in-plane modulus from the velocity calculated from the in-plane displacement signal associated to the S_0 Lamb wave mode.

10 38. An apparatus as described in claim 22 whereby the second location overlaps the first location and whereby the analyzing means first derives the through-thickness velocity from the through-thickness echoes and hence the compression modulus or compressibility from the through-thickness velocity.

39. An apparatus as described in claim 22 further including means for providing

15 several detection locations to measure simultaneously the velocity of S_0 and A_0 modes in various directions and to obtain the angular distribution of tension and tensile modulus.

40. An apparatus as described in claim 22 further including means for providing several generation locations to measure simultaneously the velocity of S_0 and A_0

20 modes in various directions and to obtain the angular distribution of tension and tensile modulus.

41. An apparatus as described in claim 22 whereby first laser is a carbon dioxide laser.

42. An apparatus as described in claim 22 whereby first laser has a wavelength

25 suitable to be absorbed by an OH band of the sheet material.

43. An apparatus as described in claim 22 whereby the interferometric means is a confocal Fabry-Perot interferometer.

44. An apparatus as described in claim 22 whereby the interferometric means is based on two-wave mixing in a non-linear optical material.

30 45. An apparatus as described in claim 22 whereby the interferometric means is based on the photoelectromotive force effect in an optical material.

46. An apparatus as described in claim 22 whereby the first beam has properties preventing a damage of the sheet affecting a further use thereof.
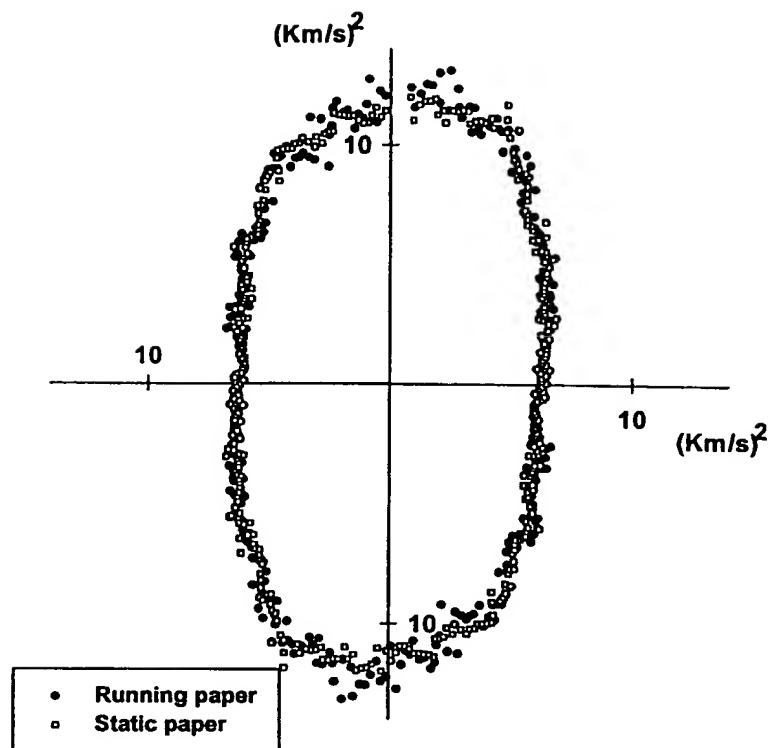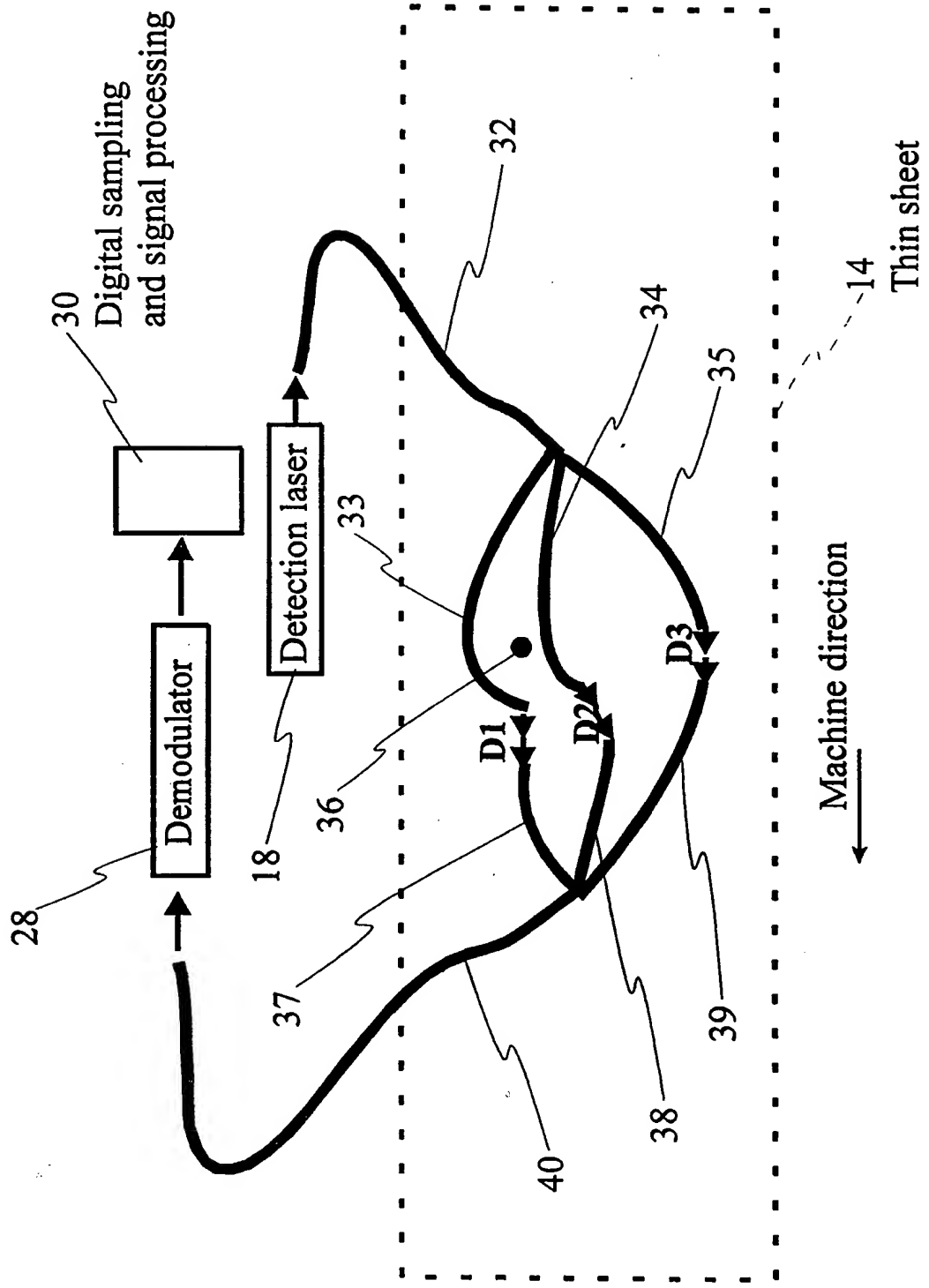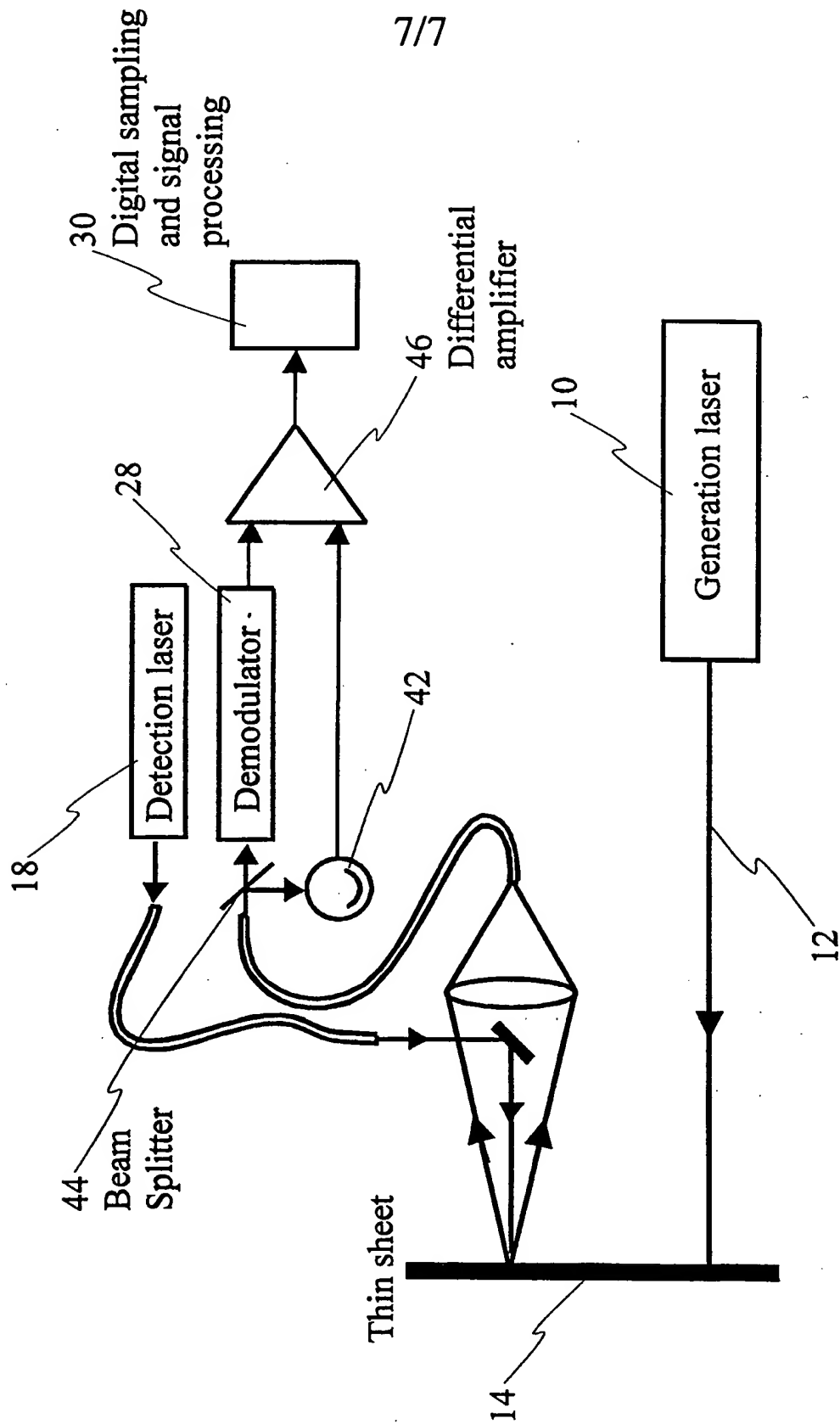
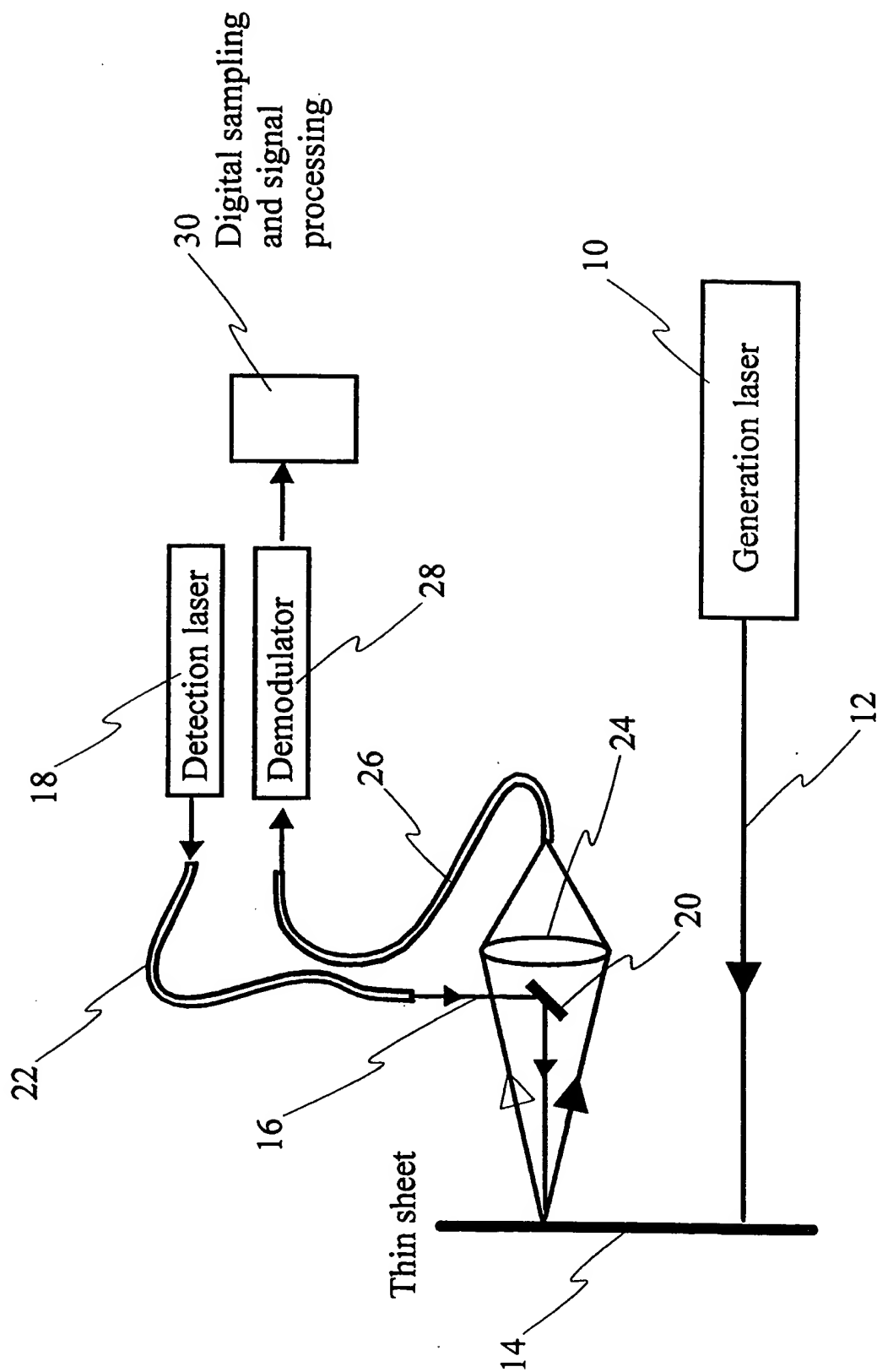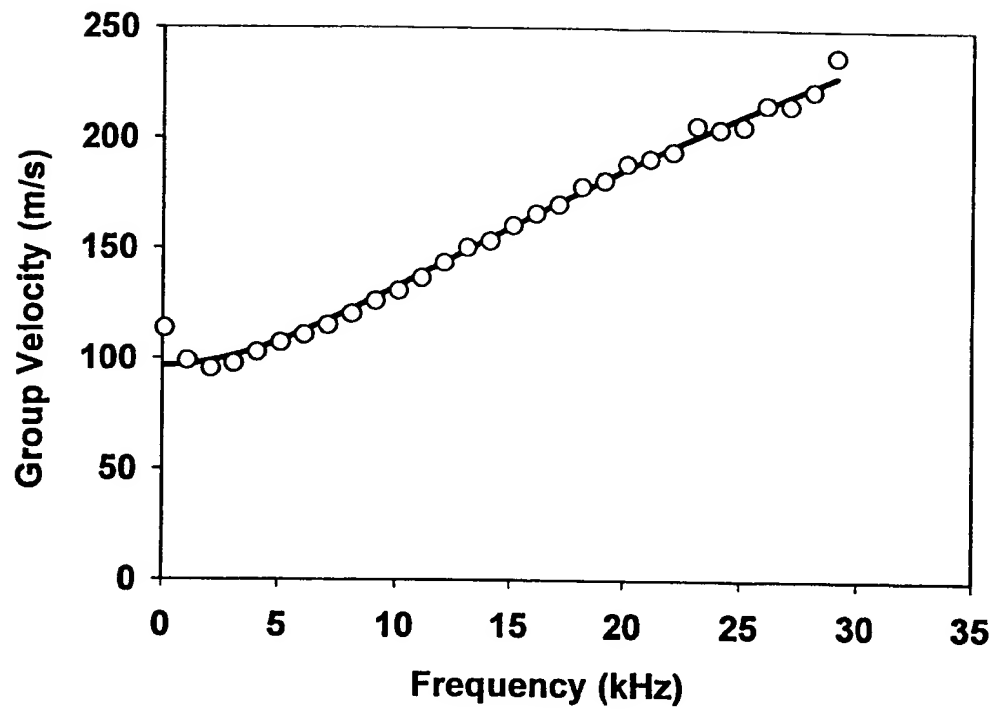Fig. 1

Fig. 2

Fig. 3

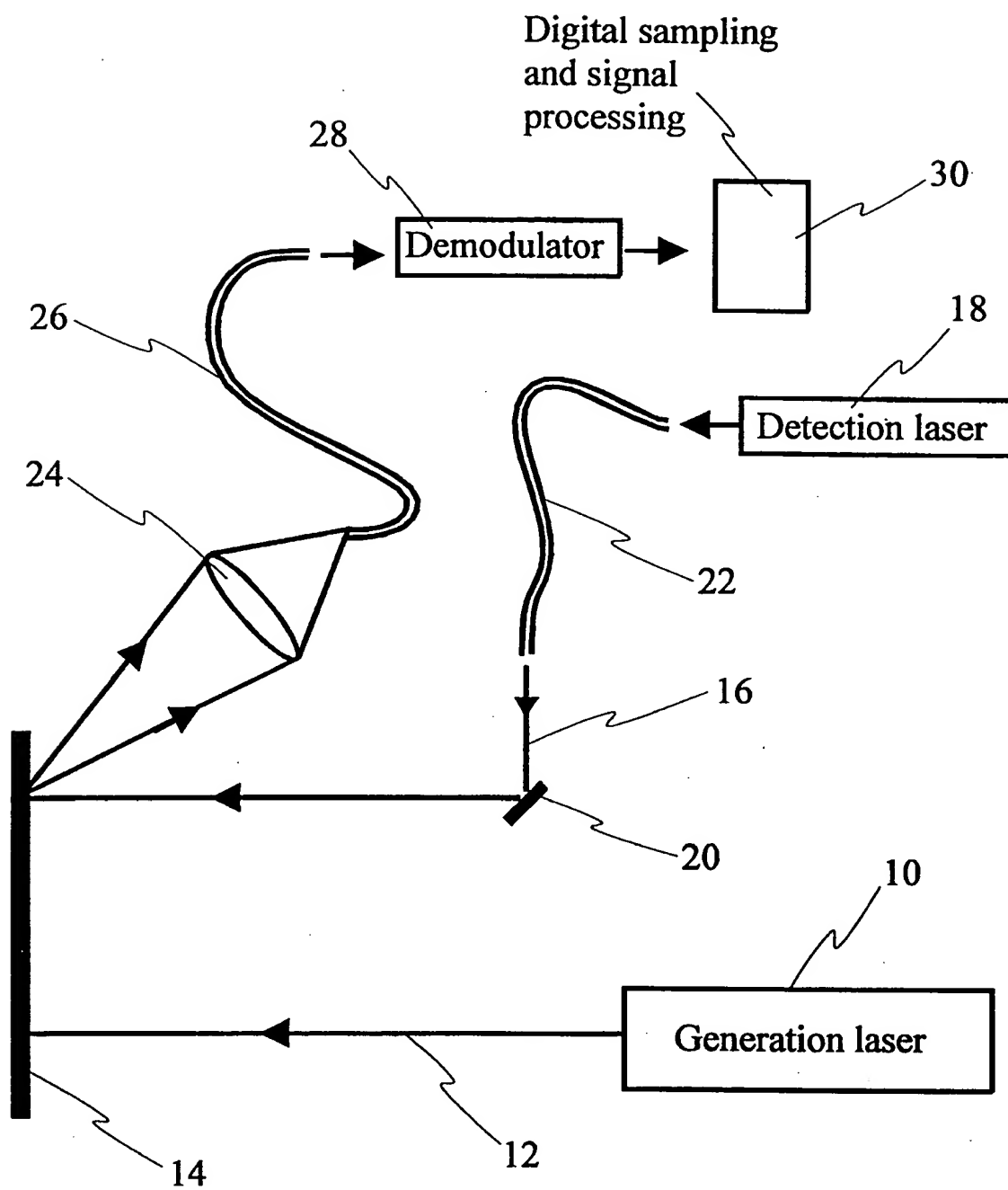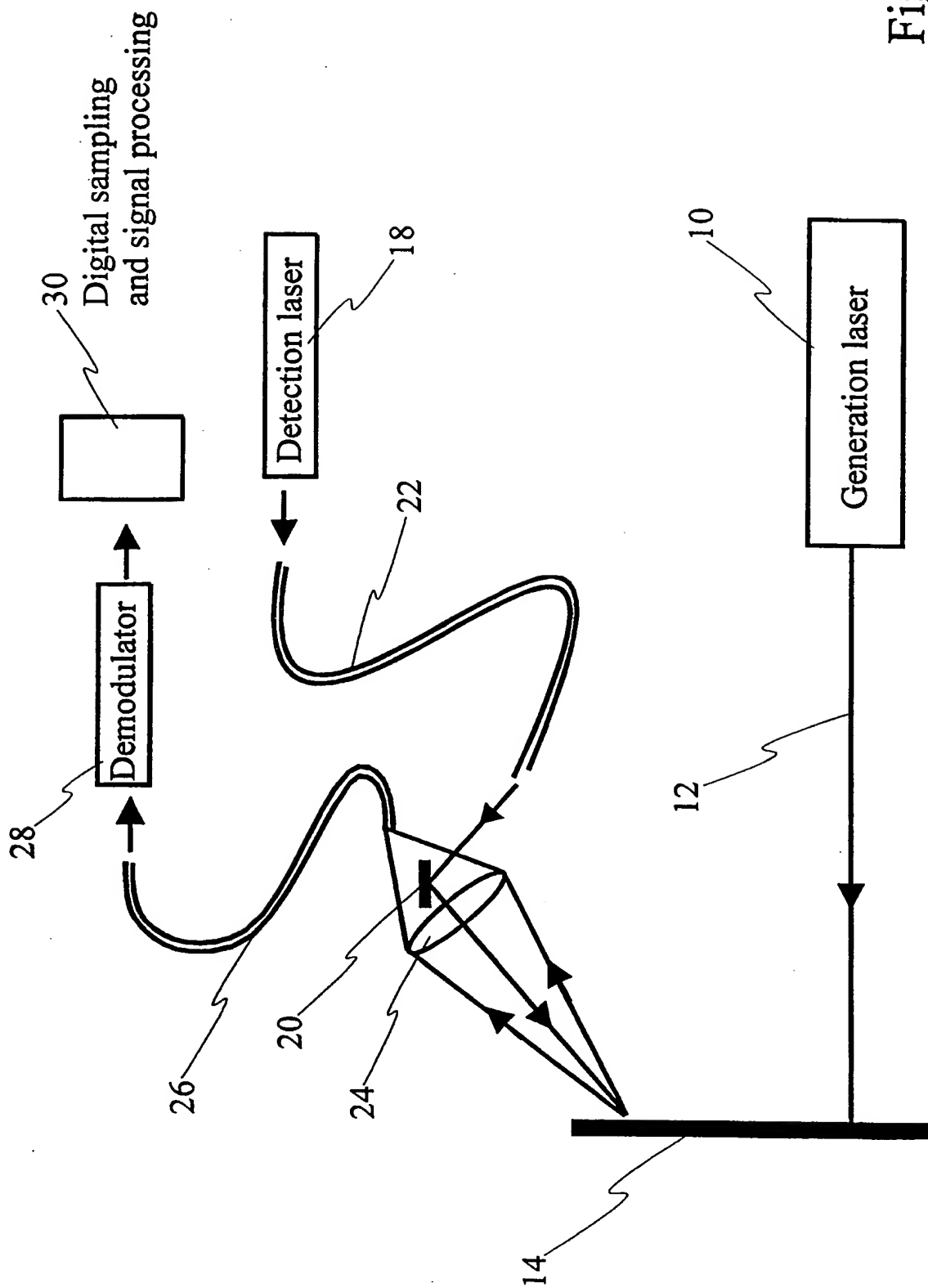Fig. 4

Digital sampling
and signal processing

30

Detection laser

18

Demodulator

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Generation laser

12

14

Fig. 5

Fig. 6

Fig. 7

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7   G01L5/04   G01N29/24   G01N33/34   D21F7/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7   G01L   G01N   D21F   G01H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 814 730 A (IPST AND GIT) 29 September 1998 (1998-09-29) cited in the application	1
Y	figure 2	2,22
Y	US 5 025 665 A (ELSAG) 25 June 1991 (1991-06-25) cited in the application column 3, line 19 - line 26; figures 1,3	2,22
Y	US 4 966 459 A (CPDL) 30 October 1990 (1990-10-30) cited in the application column 2, line 33 - line 41	2,22
A	US 5 608 166 A (NRCC) 4 March 1997 (1997-03-04) column 1, line 33 - line 35; figure 5	1,2,22

☐ Further documents are listed in the continuation of box C.　　　|X| Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
7 February 2000	17/02/2000

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